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Currents: Weak and Electromagnetic

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The currents that figure in electromagnetic and weak interactions of hadrons have acquired a substantial status in recent years as basic theoretical entities, very much in the way that various elementary particles used to be basic before there were so many of them. This conference is mostly concerned with the hadron electromagnetic current and detailed features of reaction processes which it induces. But my assigned task here is to remind you how matters stand for the physics of weak currents and to remind you of the general connections that are supposed to relate the two branches of physics, according to present lore.

The connections are best brought out in the first instance if we consider, for the electromagnetic case, processes involving hadrons and a single electron or muon pair, e.g., processes such as

$$e + \alpha \rightarrow e + \beta \quad \text{or} \quad \alpha \rightarrow \beta + e + \bar{e}$$

where α and β are systems of hadrons. To lowest order in the fine structure constant one is dealing with processes involving a single off-shell photon

$$"\gamma" + \alpha \rightarrow \beta, \quad \alpha \rightarrow \beta + "\gamma",$$

where, depending on the situation, the momentum vector q of the virtual photon is either space-like or time-like. Real photon processes in this way of looking at things represent a special case, where $q^2 = 0$. To lowest order in the fine structure constant the amplitude for, say, the reaction $e + \alpha \rightarrow e' + \beta$, is given by

$$e^2 \langle \beta | J_\lambda^{em} | \alpha \rangle \frac{i}{q^2} \bar{u}(e') \gamma_\lambda \bar{u}(e), \tag{1}$$

where J_λ^{em} is the hadronic part of the electromagnetic current and where the states $| \alpha >$ and $| \beta >$ are determined purely by the strong interactions. The electron parameters in the above expression appear in a simple, known factor. For the rest, the physics is in the matrix element $\langle \beta | J_\lambda^{em} | \alpha \rangle$, an object which belongs to the strong interactions and shares all the complexities of that subject.

So much for electromagnetism at the moment. For the weak interactions, we shall focus here on the so-called semi-leptonic reactions. On present evidence these are adequately described to lowest order in an effectively local current-current interaction of the form

$$H_{\text{semi-leptonic}} = \frac{G}{\sqrt{2}} J_\lambda \ell_\lambda^\dagger + \text{h.c.}, \tag{2}$$

where ℓ_λ is the weak lepton current

$$\ell_\lambda = i \sum_{\ell = e, \mu} \bar{\psi}_{\nu_\ell} \gamma_\lambda (1 + \gamma_5) \psi_\ell \tag{3}$$

and J_λ is a charge raising hadron current ($J_\lambda^\dagger$ is charge lowering), containing both vector and axial vector parts.

To lowest order in the weak coupling constant G, the amplitude for a semi-leptonic process such as $\nu_\ell + \alpha \rightarrow \ell + \beta$ is given by

$$\frac{G}{\sqrt{2}} < \beta \,|\, J_\lambda \,|\, \alpha > \ \bar{u}_\ell \ \gamma_\lambda (1 - \gamma_5) \ \bar{u}_\nu . \tag{4}$$

As in the electromagnetic case, the lepton terms again factor out in a simple way, the remaining physics being confined to the hadron matrix element $< \beta \,|\, J_\lambda \,|\, \alpha >$. At their respective lowest order levels there is evidently a considerable resemblance, at least kinematic and notational, between the electromagnetic and weak semi-leptonic processes. In the one case strong interactions are being probed by the electromagnetic current, which is neutral and which transforms like a 4-vector; in the other case, by the charged, vector and axial vector weak currents.

It may be that the currents will best be understood some day in terms of their structure with respect to more elementary constructs, e.g., the "fundamental" quantum fields of hadron physics. However, while we are all waiting for this to happen, it is worthwhile to speculate directly on the currents; i.e., to look for abstract but tenable characterizations which may transcend the dynamical details of hadron physics. One obvious mode of characterization, which in a sense is preliminary to all others, has to do with the behavior of the currents under various strong interaction symmetries. Let me turn first to this, in particular for the weak currents.

Classified with respect to isospin, strangeness, and G parity (where appropriate), it is well established that the weak vector and axial vector currents have pieces symbolized in the following equations:

$$J_\lambda = V_\lambda + A_\lambda$$

$$V_\lambda = \cos\theta_C\, V_\lambda(I=1,\ I_z=1,\ S=0,\ G=1) + \sin\theta_C\, V_\lambda(I=\tfrac{1}{2},\ I_z=\tfrac{1}{2},\ S=1) + \ldots$$

$$A_\lambda = \cos\theta_C\, A_\lambda(I=1,\ I_z=1,\ S=0,\ G=-1) + \sin\theta_C\, A_\lambda(I=\tfrac{1}{2},\ I_z=\tfrac{1}{2},\ S=1) + \ldots \tag{5}$$

The Cabibbo factors $\cos\theta_C$ and $\sin\theta_C$ are of course gratuitous at this stage, until independent scales can be given for the currents which they multiply. This will be taken up shortly. For the moment, notice that the strangeness changing currents given above correspond to the rule $\Delta S = \Delta Q$; and for the strangeness conserving currents, notice that the G parity properties correspond to "first class" in Weinberg's classification.[1]

The dots at the end of Eqs. (5) are meant to remind us of additional open possibilities. After all, what we know about the quantum numbers of currents has so far come mainly from study of decay processes, where opportunities for getting at even mildly exotic quantum numbers are highly limited. For what accessible day process could one see the workings of say, a $\Delta S = 5$ current? Or a $\Delta S = 0$, $I = 5$ current, etc.? Less exotic is the question of second class currents, which in fact have received a lot of attention recently. These currents are perhaps best looked for in high energy neutrino processes. But they could also show themselves in nuclear β decay, although kinematic inhibitions here make the search a difficult one. Some tantalizing hints may nevertheless have been observed. To see what's involved, consider a mirror pair of strangeness conserving decay processes

$$\alpha \to \beta + e^- + \nu \qquad \text{vs.} \qquad \tilde{\alpha} \to \tilde{\beta} + e^+ + \bar{\nu} \tag{6}$$

where $|\tilde{\alpha}\rangle = e^{i\pi I_2}|\alpha\rangle$ is the mirror of $|\alpha\rangle$; $\tilde{\beta}\rangle$, the mirror of $|\beta\rangle$. The amplitudes for the two processes are proportional respectively, to the matrix elements

$$\langle\beta|J_\lambda|\alpha\rangle \quad \text{and} \quad \langle\tilde{\beta}|J_\lambda^\dagger|\tilde{\alpha}\rangle .$$

In the absence of second class currents, and employing CPT invariance, one readily shows that

$$\langle\beta|J_\lambda|\alpha\rangle = \langle\tilde{\beta}|J_\lambda^\dagger|\tilde{\alpha}\rangle , \tag{7}$$

provided electromagnetic violations of G parity conservation can be neglected. This equation implies a detailed relation between the spectra for the two processes; and more grossly, an equality between their ft values. In surveying the experimental evidence, Wilkinson and Alburger[2] have called attention to a systematic pattern of ft - value discrepancies, with

$(ft)^{+}$ exceeding $(ft)^{-}$ by as much as 20% in some cases. The existence of these discrepancies does not seem to be in any experimental doubt. But the influence of electromagnetic corrections will have to be clarified before any firm conclusions can be drawn about second class currents. Or better, one will have to look at more detailed spectral effects for very large discrepancies in small terms - discrepancies too large to be attributed in any reasonable way to an electromagnetic origin.[3] Still better, one should compare neutrino and anti-neutrino strangeness conserving processes on a target which is its own mirror, e.g., deuterium, carbon, etc:

$$\begin{aligned} \nu_\mu + \alpha &\rightarrow \mu^- + X, \qquad |\tilde{\alpha}\rangle = |\alpha\rangle \\ \bar{\nu}_\mu + \alpha &\rightarrow \mu^+ + \tilde{X}. \qquad \Delta S = 0 \end{aligned} \tag{8}$$

In the absence of second class currents, the structure functions $W_i^{(\nu)}$ and $W_i^{(\bar{\nu})}$ are supposed to be equal

$$W_i^{(\nu)} = W_i^{(\bar{\nu})} \tag{8'}$$

Let us next turn to the hadron electromagnetic current and its classification with respect to strong interaction symmetries. It is of course very well established that this current contains isoscalar and isovector pieces, both of them odd under charge conjugation:

$$J_\lambda^{em} = V_\lambda^{em}(I=1,\ I_z=0,\ C=-1) + V_\lambda^{em}(I=0,\ I_z=0,\ C=-1) + \ldots \quad (9)$$

This used to be all, but in recent years some interesting additional possibilities have been proposed. For one thing, in connection with the discovery of CP violation in neutral K meson decays, there is the idea that this symmetry violation arises from a component of the electromagnetic current which is even under charge conjugation; i. e., the electromagnetic interactions of hadrons on this picture might display substantial C- and T- violation.[4] A number of experimental searches were immediately stimulated by the proposal; and inevitably, some positive indications showed up here and there in the early rounds. However, by last year the list had been reduced to two effects: a 1.5 ± 0.5% asymmetry between π^+ and π^- reported by W. Lee and collaborators[5] in the spectrum of $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ decay;and a 2-3 standard deviation breakdown of detailed balance in $n + p \rightleftarrows d + \gamma$, reported by Bartlett, Goulianos, and collaborators.[6] The η decay experiment was subsequently repeated, however, and the asymmetry is now reduced to A = 0.03 ± 0.2%.[7] Moreover, the detailed balance breakdown in $n + p \rightleftarrows d + \gamma$ seems to have gone away in the new measurements by Bartlett, Goulianos, et al.,[8] and in the experiment of Schrock, et al.[9]

But wait! In the meantime new evidence has been reported for what could be a very substantial breakdown of detailed balance in $\pi^- + p \rightleftarrows \gamma + n$. The differential cross section for the forward reaction has been measured at center of mass energies 1337 MeV and 1245 MeV by Berardo et al.[10]

Information on the reverse interaction has unfortunately to be extracted from experiments on deuterium, something which involves problematic corrections. Some confidence on this point is claimed from the fact that detailed balance does in fact check out well for the higher energy (1337 MeV). But in the N^* region, at 1245 MeV, a substantial breakdown of detailed balance in reported: for $\theta_{\gamma\pi} \geq 90^0$, $d\sigma(\rightarrow)$ is systematically smaller than $d\sigma(\leftarrow)$ by $\sim$ 30%! It will be important to repeat the measurements, and subject the deuteron corrections to careful scrutiny.

Another issue for the electromagnetic current has to do with its isospin properties; namely, are their components with $I > 1$? It's not so easy to come up with tests which have the promise of being both practical and decisive. The prospects are perhaps best in reaction such as $e^+ + e^- \rightarrow \pi^+ + \pi^- + \pi^0$ (asymmetry between π^0 and $\pi^\pm$ spectra). Nevertheless, some hint of isotensor current effects in photomeson production in the (3, 3) resonance region has been perceived and extensively discussed by Sanda and Shaw.[11] One is dealing here with a collection of four reactions:

$$\begin{aligned} &\gamma+p \rightarrow n+\pi^+ && \text{(a)} \\ &\gamma=p \rightarrow p+\pi^0 && \text{(b)} \\ &\gamma+n \rightarrow p+\pi^- && \text{(c)} \\ &\gamma=n \rightarrow n+\pi^0. && \text{(d)} \end{aligned} \qquad (10)$$

In the absence of isotensor currents they are described by only three independent (but complex) amplitudes, classified by isotopic spin of the current component and of the final pi-nucleon state. Moreover, if T invariance holds, the multipole amplitudes below the threshold for two pion production have well enough known phases, determined by pi-nucleon scattering. But there is clearly no model independent way to test for isotensor currents without employing data on all four reactions. Unfortunately information on reaction (d) can only come from deuterium experiments, with all the attendent theoretical uncertanties; and in any case, such data is lacking in the N^* region.

The claimed evidence for isotensor currents therefore rests on model dependent considerations, applied in particular to reactions (a) and (c) (or better, $\pi^- + p \to \gamma + n$ if one accepts T invariance), in the N^* region. The key idea is this. Consider the difference $\Delta = \sigma_T(\gamma+n \to \pi^- + p) - \sigma_T(\gamma+p \to \pi^+ + n)$ with respect to its energy dependence in the resonance region. For each of the above cross sections the dominant term is the square $|M^3_{1+}|^2$ of the magnetic dipole amplitude; but the squared contribution cancels out in Δ if isotensor currents are absent, leading one to expect only smallish bumps near the resonance. The experiments seem however to suggest somewhat bigger bumps, such as might arise from substantial $I = 1$, $I = 2$ interference. For the rest, the quantitative estimate of expectations on the conventional picture rests rather heavily on dispersion theoretic models. The subject is too complex to pursue any further here, but I hope in the discussion that we can hear from the experts on this important matter.

For the remaining discussion I will stick to the well established currents and take up their further properties and connections. An important first connection between the weak and electromagnetic currents is provided by the familiar CVC hypothesis. This places the weak $\Delta S = 0$ vector currents $V_\lambda(I=1)$ and $V_\lambda^\dagger(I=1)$ in the same isotopic triplet as the isovector electromagnetic current $V_\lambda^{em}(I=1)$, in the same way that the three vector mesons ρ^+, ρ^-, ρ^0 belong to a common triplet. The CVC hypothesis provides a scale for $V_\lambda(I=1)$ and it of course implies also that this current is conserved. It will be an important objective of high energy neutrino physics to subject CVC to more extensive testing than has so far been possible in nuclear β decay, where, however, the hypothesis seems to be sustained. In the framework of SU_3 still further connections among the various currents are provided by Cabibbo's conjecture. According to this, all the weak axial vector currents belong to a common SU_3 octet; and all the weak and electromagnetic vector currents again belong to a common octet. Insofar as SU_3 is really a good strong interaction symmetry this highly unifying picture sets the relative scales within each octet in an objective way. The scheme meets with considerable success in correlating various hyperon β decays, even, surprisingly, when one ignores SU_3 symmetry violations in the strong interactions.

The SU_3 classification, as said, is directly meaningful only insofar as this symmetry is well respected by the strong interactions. A much more abstract characterization of the currents in terms of SU_3, indeed of $SU_3 \times SU_3$, was introduced by Gell-Mann in his celebrated equal time current commutator algebra. In our discussion so far we have been speculating directly on the currents, without reference to their underlying structure in terms of "fundamental" quantum fields. The Gell-Mann algebra can similarly be postulated in a direct way. Nevertheless, in this and in related developments, models have proved useful, in part for motivation and in part as checks on formal (at least) consistency with general field theoretic principles.

In its most far reaching version, the equal time commutator algebra is often based on the quark model of currents. That is, labeling the various currents in the standard way by an octet index, one takes for the vector and axial vector currents

$$V_\mu^a = i \bar{\psi} \gamma_\mu \frac{\lambda^a}{2} \psi ,$$

$$V_\mu^a = i \bar{\psi} \gamma_\mu \gamma_5 \frac{\lambda^a}{2} \psi ,$$

where ψ is the quark field and the λ^a $(a = 1, 2, \ldots 8)$ are standard SU_3 matrices. The equal time anti-commutation relations for the quark fields are supposed to be given by the usual canonical rules. One can then readily work out the <u>formal</u> equal time current commutations, which are independent of the details of the strong interactions and of SU_3 breakdown there.

The idea now is to postulate the equal time commutators for the real world, without regard to the physical reality of quarks. (I am not taking up here certain important but technical qualifications concerning so-called Schwinger terms). For the rest the art is to extract the physical implications of these abstract commutation relations, ideally with a minimum of further assumptions. This has been a major industry for several years now. Among the relatively clean predictions one may mention: for photo processes, the Cabibbo-Radicati sum rule, reasonably well supported by present data; and for neutrino processes, the Adler sum rule, still untested. Further predictions emerge when current algebra is adjoined to the famous PCAC hypothesis. The latter represents yet another speculative but interesting property of currents, this time for the strangeness conserving axial vector currents. The hypothesis has its own tests, independent of current algebra. Moreover, the two doctrines turn out to be well matched; taken together, they lead to striking additional predictions, for example the one embodied in the well-known Adler-Weisberger formula. There is no space here for a general review of the situation, or for discussion of yet another PCAC-like conjecture - vector dominance. But it should be clear by now why the currents have become such interesting theoretical entities.

Instead, let me turn finally to the newest development, one which centers on the structure of current commutators near the light cone. Interest in this very formal-sounding question has been stimulated by the striking experimental results discovered in the SLAC-MIT experiments[12] on deep inelastic electron scattering, and by hints of correspondingly remarkable features in high energy neutrino reactions. Let us carry out the discussion on the latter example, where we consider processes of the sort

$$\nu + N \to \mu^- + X.$$

Here N is, say, a nucleon target, of four momentum p; and X is a system of hadrons. The four momentum difference between incident and outgoing leptons is q, and their laboratory energies are ϵ and ϵ', θ being the angle between the leptons. In computing the inclusive cross section, summed over all hadrons states and averaged over target spins, one encounters the tensor

$$W_{\nu\mu} = (2\pi)^3 \sum_X \langle p| J_\nu^\dagger | X\rangle \langle X| J_\mu | p\rangle \, \delta\, (p_X - p - q). \tag{11}$$

This can be decomposed according to

$$\begin{aligned} W_{\nu\mu} = {} & W_1\left(\delta_{\nu\mu} - \frac{q_\nu q_\mu}{q^2}\right) + \frac{W_2}{m^2}\left(p_\nu - \frac{p\cdot q}{q^2} q_\nu\right)\left(p_\mu - \frac{p\cdot q}{q^2} q_\mu\right) \\ & + \frac{1}{2}\frac{W_3}{m^2}\epsilon_{\nu\mu\alpha\beta}\, q_\alpha p_\beta + \frac{W_4}{m^2} q_\nu q_\mu + \frac{W_5}{m^2}(p_\nu q_\mu + q_\nu p_\mu) \\ & + \frac{W_6}{m^2}(p_\nu q_\mu - q_\nu p_\mu). \end{aligned} \tag{12}$$

The structure functions W_i depend on the two variables q^2 and $\nu = \epsilon - \epsilon' = -q \cdot p / m^2$. W_3 arises from vector-axial vector interference and has no counterpart in electroproduction. The structure functions $W_{4,5,6}$, which similarly have no counterpart in electroproduction, make only small contributions to the neutrino cross section, since the contraction of q_λ with the lepton current $\bar{u}_\mu \gamma_\lambda (1 + \gamma_5) u_\nu$ is proportional to the (small) muon mass. This is a pity; these functions carry potentially interesting information, W_6 in particular providing a measure of time reversal violation. Ignoring the lepton mass, however, one finds for ν or $\bar{\nu}$ processes the well known cross section formula

$$\frac{\partial \sigma}{\partial q^2 \partial \nu} = \frac{G^2}{2\pi m} \frac{\epsilon'}{\epsilon} \left\{ 2W_1^{\binom{\nu}{\bar{\nu}}} \sin^2 \frac{\theta}{2} + W_2^{\binom{\nu}{\bar{\nu}}} \cos^2 \frac{\theta}{2} \mp \left(\frac{\epsilon + \epsilon'}{m} \right) W_3^{\binom{\nu}{\bar{\nu}}} \sin^2 \frac{\theta}{2} \right\} \tag{13}$$

For electroproduction, $e + N \rightarrow e + X$, the whole analysis repeats itself, except of course that $W_3^{(em)} = 0$ and $G^2 \rightarrow 8\pi^2 \alpha^2 / (q^2)^2$.

All of this is familiar enough kinematics. The physics is in the structure functions and their dependence on the variables ν and q^2. Among the various theoretical expectations, there is one which stands out as a direct and clean test of the local equal-time commutator algebra of Gell-Mann; namely, the Adler sum rule[13]

$$\int_0^\infty \frac{d\nu}{m}\left\{W_2^{(\bar{\nu})}(\nu, q^2) - W_2^{(\nu)}(\nu, q^2)\right\} =$$
$$4I_3 \cos^2\theta_C + \left(2I_3 + 3Y\right)\sin^2\theta_C\,, \quad (14)$$

where I_3 and Y are the isospin and hypercharge quantum numbers of the target. Apart from this, much of the contemporary theorizing focuses on the behavior of the structure functions in the Bjorken limit

$$q^2,\ \nu \to \infty \qquad \omega = \frac{q^2}{2m\nu} \text{ fixed}, \qquad 0 \leq \omega \leq 1. \qquad (15)$$

Here it is convenient to define

$$F_1 = W_1,\ F_2 = \frac{\nu}{m} W_2,\ F_3 = \frac{\nu}{m} W_3 \qquad (16)$$

and to regard the F_i as functions of q^2 and w.

It was Bjorken's conjecture that the F_i scale, i.e., approach finite functions of ω in the limit $q^2 \to \infty$, ω fixed. This scaling hypothesis seems to be supported by present data on electroproduction, where, moreover, the indication for the limiting functions is that $F_2^{em} \approx 2\omega F_1^{em}$ $(\sigma_L/\sigma_T \approx 0)$. For neutrino processes the situation is experimentally less clear, but the linear growth with energy observed for the total neutrino cross section is again compatible with scaling. Averaged over neutrons and protons one finds experimentally for large energies[14]

$$\sigma_T^{(\nu)} \approx (0.52 \pm 0.13) \ \frac{G^2 m \epsilon}{\pi} \ . \tag{17}$$

In form and magnitude this is remarkably similar to what one would find for quasielastic scattering on point particles.

A physical picture which incorporates scaling is provided by the very popular parton model.[15] From a more abstract point of view, however, one may notice that it is the light cone structure of current commutators that is being probed in the Bjorken limit, $q^2 \to \infty$, ω fixed. The fact that scaling seems to occur in this limit suggests that the light cone commutator is somehow simple, and therefore a subject worthy of attention. To see how it is that the light cone commutator comes into play, let's first observe that the tensor $W_{\nu\mu}$ can be expressed in the form

$$W_{\nu\mu} = \frac{1}{2\pi} \int dx e^{-iq\cdot x} \langle p \,|\, [\, J_\nu^\dagger(x), \ J_\mu(0) \,] \,|\, p\rangle \tag{18}$$

Now go to the target rest frame, where $q_0 = \nu$; and let q be directed along, say, the 3-axis. For q^2 large, ω fixed, one has

$$q_3 \to q_0 + m\omega .$$

The exponential factor in Eq. (18) can be written

$$\exp \frac{i}{2} (q_0 - q_3)(x_0 + x_3) + (q_0 + q_3)(x_0 - x_3) \quad .$$

Owing to oscillations of the exponential, one expects the chief contributions in the integral to come from the region where

$$|x_0 + x_3| \lesssim \frac{1}{m\omega}, \quad |x_0 - x_3| \lesssim \frac{1}{2q_0} \quad .$$

Since the commutator vanishes unless

$$-x^2 \equiv x_0^2 - x_3^2 - x_\perp^2 \geq 0$$

we see that the light cone dominates in the Bjorken limit:

$$-x^2 \approx \frac{1}{2mq_0\omega} \xrightarrow[q_0 \to \infty]{} 0$$

Scaling supports the hope that the singularity structure is simple on the light cone.

Although the parton model does not employ the abstract language of light cone commutators, it is evidently dealing with that subject. In appealing to field theoretic models for guidance on the light cone, it is important to keep in mind a contrast with the situation encountered for <u>equal time</u> commutators. In the latter case the commutators emerge, formally at least, without reference to the strong interactions, once the currents have been expressed in terms of canonical fields. The light cone commutators, on the other hand, depend not only on the structure of the currents but also on the details of the strong interactions. The situation is therefore more heavily model dependent. Of course this has not stopped people from speculating; and at the end, one can always extract his favorite conjectures and then throw away the models.

For a start, following Fritzch and Gell-Mann,[16] it seems natural to appeal to the completely free field quark model. The calculations here are straightforward, though lengthy. For the currents (or conveniently, for certain combinations of definite chirality) take

$$J_{\mu}^{a,\pm}(x) = i\bar{\psi}(x)\gamma_{\mu}(1\pm\gamma_5)\frac{\lambda^a}{2}\psi(x). \tag{19}$$

Then one finds near the light cone

$$\begin{aligned}[J_{\nu}^{a,\pm}(x), J_{\mu}^{b,\pm}(y)] \xrightarrow[(x-y)^2\to 0]{} \; & i f_{abc}\Big\{S_{\nu}^{c,\pm}(x,y)\,\delta_{\mu\alpha} + S_{\mu}^{c,\pm}(x,y)\,\delta_{\nu\alpha} \\ & -\delta_{\mu\nu}S_{\alpha}^{c,\pm}(x,y) \mp \epsilon_{\nu\alpha\mu\rho}A_{\rho}^{c,\pm}(x,y)\Big\}\frac{\partial}{\partial x_{\alpha}}D(x-y). \\ & + d_{abc}\Big\{S \longleftrightarrow A\Big\}\frac{\partial}{\partial x_{\alpha}}D(x-y), \end{aligned} \tag{20}$$

where

$$D(z) = - \frac{1}{2\pi} \epsilon(z_0)\ \delta(z^2). \tag{21}$$

The bilocal operator S and A are given by

$$\begin{aligned} S_\mu^{a,\pm}(x,y) &= i\bar{\psi}(x)\ \gamma_\mu\ (1\pm\gamma_5)\ \frac{\lambda^a}{2}\ \psi(y)\ +\ (x \leftrightarrow y), \\ A_\mu^{a,\pm}(x,y) &= i\bar{\psi}(x)\ \gamma_\mu\ (1\pm\gamma_5)\ \frac{\lambda^a}{2}\ \psi(y)\ -\ (x \leftrightarrow y). \end{aligned} \tag{22}$$

The idea now is to adopt the singularity, SU_3, and tensor structures of Eq. (21), taking this as a conjecture for the real world and dropping the more detailed specifics of Eqs. (22). The general structure of Eq. (21) is already in itself informative and incorporates the results of parton models which base themselves on identification of parton with quarks. That is, one finds the well known results[17]

$$\begin{aligned} 2\omega\ F_1(\omega) &= F_2(\omega) \\ F_3^{(\nu p)} - F_3^{(\nu n)} &= 12\left(F_1^{\gamma p} - F_1^{\gamma n}\right) \\ F_1^{(\gamma p)} + F_1^{(\gamma n)} &> \frac{5}{18}\left(F_1^{(\nu p)} + F_1^{\nu n)}\right), \end{aligned} \tag{23}$$

and so on.

Before adopting Eq. (21) as a pre-standing conjecture, one of course wishes to know whether it is peculiar to the free quark model or whether, instead, it survives in some class, at least, of non-trivial models with strong interactions switched on. It seems that the structure does survive, formally at least, in models where the strong interactions among quarks are mediated by isosinglet vector or spinless gluons. By "formal" I mean: according to manipulations based on canonical equal time commutation and anti-commutation relations among the gluon[18] and quark fields.

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